

THE NEAR AND LONG TERM PULSE POWER REQUIREMENT FOR LASER DRIVEN INERTIAL CONFINEMENT FUSION*

W.L. Gagnon

Lawrence Livermore Laboratory
Livermore, California 94550ABSTRACT

Inertial confinement fusion research is being vigorously pursued at the Lawrence Livermore Laboratory and at other laboratories throughout the world.

At the Lawrence Livermore Laboratory, major emphasis has been placed upon the development of large, Nd:glass laser systems in order to address the basic physics issues associated with light driven fusion targets.

A parallel program is directed toward the development of lasers which exhibit higher efficiencies and shorter wavelengths and are thus more suitable as drivers for fusion power plants. This paper discusses the pulse power technology which has been developed to meet the near and far term needs of the laser fusion program at Livermore.

Introduction

The Laser Fusion Program^{1,2,3,4} is making rapid progress toward achieving thermonuclear fusion. One of the keys to this rapid progress is the sequence of laser facilities with increasing power (Fig. 1) developed at LLL in pursuit of the laser fusion program goals. Janus has yielded an extensive catalogue of laser fusion data and measurements of alpha particles demonstrating the TN nature of the implosion reaction, thus achieving the first milestone. Cyclops focused 0.6 TW on target from a single laser chain and has served as a prototype for the large, multi-arm Shiva and

*Work performed under the auspices of the U.S. Dept. of Energy by the Lawrence Livermore Lab. under contract no. W-7405-Eng. 48.

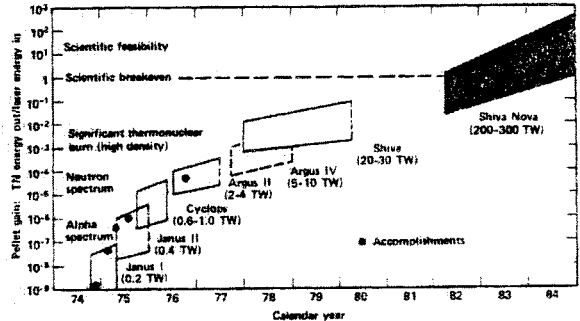


Fig. 1: LLL laser-fusion yield projections and laser systems. A series of increasingly powerful Nd:glass lasers has been built for laser fusion experiments.

and Argus systems. Argus has operated at greater than 4 TW from two laser chains and has now produced more than one billion neutrons on a single shot, with a pellet gain of 2×10^{-5} . Shiva, a 20 arm, 20 TW system has been operational since February 1978 and has produced a neutron yield of 2.7×10^{10} and compressions of 50X liquid density. Nova⁵, currently under construction, will produce several hundred TW of output power and demonstrate the feasibility of net energy gain with high gain microexplosions.

Each laser system in this progression has increased in both size and complexity. The pulse power hardware represents about one-quarter of the total project cost for each of these systems. For Shiva, this amounted to \$7M and for Nova we expect the pulser power system cost to exceed \$30M. We have developed reliable, cost effective, and scalable pulse power technology specifically suited to meet the needs of large Nd:glass lasers.

Report Documentation Page				Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE JUN 1979		2. REPORT TYPE N/A		3. DATES COVERED -		
4. TITLE AND SUBTITLE The Near And Long Term Pulse Requirement For Laser Driven Inertial Confinement Fusion				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lawrence Livermore Laboratory Livermore, California 94550				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited						
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License						
14. ABSTRACT Inertial confinement fusion research is being vigorously pursued at the Lawrence Livermore Laboratory and at other laboratories throughout the world. At the Lawrence Livermore Laboratory, major emphasis has been placed upon the development of large, Nd:glass laser systems in order to address the basic physics issues associated with light driven fusion targets.						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified				

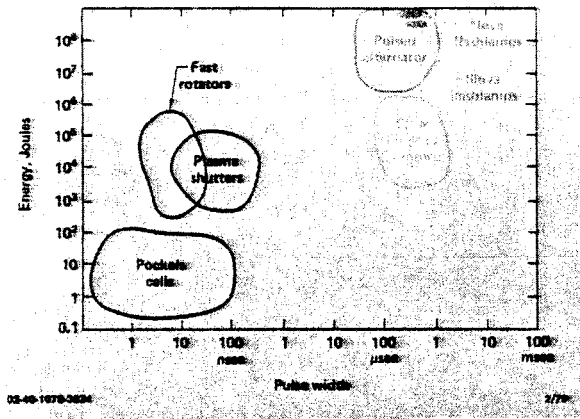


Fig. 2: Energy versus pulse width parameters for the major pulse power requirements of the laser fusion program.

Figure 2 shows the parameter space in which these pulse power requirements lie. The low energy, fast pulse circuitry addresses the needs for very fast optical switches which act to suppress amplified spontaneous emission within the laser chains, as well as to protect the laser from target reflected light. The high energy, relatively slow pulse circuitry addresses the pump requirements for these lasers, and it is in this area that most of the system cost is accounted for. This technology has been the focus of a great deal of effort^{6,7} aimed at improving both its performance and cost effectiveness.

This paper will describe the pulse power hardware which has been developed and implemented at the Lawrence Livermore Laboratory for these large laser systems, as well as discussing some promising alternative technologies which are currently under development.

Laser Pumping Requirements

The laser amplifiers (see Fig. 3) are pumped with intense broadband light output from large bore xenon flashlamps. The pump energy is delivered in approximately 500 microseconds and the peak power requirements (shown in Fig. 4) far exceed the capacity of the power grid. Thus, large capacitor banks are used as intermediate storage elements. The xenon flashlamps are nonlinear resistive

loads⁸ with two distinctly different impedance states - roughly corresponding to the time during which the lamps are in the ionization or triggering mode and the time at which the full volume of the lamp is conducting current. Typical voltage and current waveforms for a series lamp pair are shown in Fig. 5. The 35 kV voltage pulse required to initiate the ionization process is deliberately produced by the transient behavior of the bank circuitry. After full volume ionization within the lamp, the voltage and current are related by the nonlinear relationship

$$V = KI^B$$

where K is a constant determined by the geometry and gas fill pressure of the lamp. The exponent B is approximately .5 at current maximum.

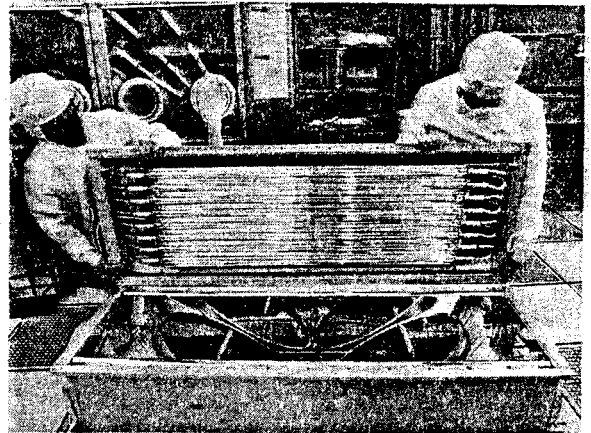


Fig. 3: A 34 cm clear aperture disk amplifier. The 16 xenon flashlamps (8 top and 8 bottom) require a total energy of 300 kJ.

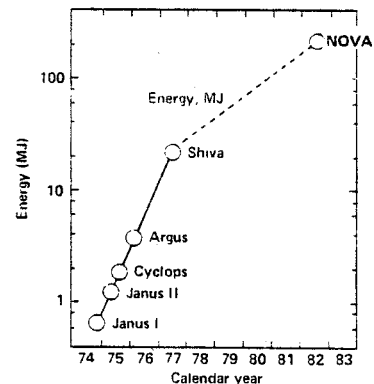


Fig. 4: The peak power requirements for lasers in the LLL Program have become increasingly large.

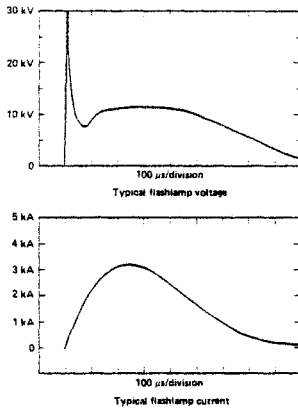


Fig. 5: Voltage and current waveforms for large bore xenon flashlamps.

The required energy per lamp depends upon the length and diameter selected. This varies from a few hundred joules for the small lamps to almost 20 kilojoules for the larger lamps. The lamps are arranged in series pairs and driven by a capacitive energy storage module which is tailored to provide the necessary energy and pulse shape. Each module contains the necessary energy storage capacitors, pulse forming inductor, dump resistors and high voltage isolating fuse. The modules are assembled as integral units and are moved with a modified fork lift. Shown in Fig. 6 is a 2.5 MJ segment of these modules as installed in the 25 MJ Shiva energy storage system.

Controls

The design of the controls and diagnostics for these pulse power systems is dictated by severe operational requirements.⁹ A large number of control and diagnostic points must be addressed and these generally lie close to the pulse power circuitry where they are exposed to transients of several kilovolts. Thus a high degree of electrical isolation is essential. The early systems (Janus, Cyclops and Argus) were small enough to allow the use of hard wired relay control systems with limited diagnostic capability. Shiva and Nova are substantially larger and these control systems must be able to carry out pre-shot diagnostics, detect real time malfunctions, and implement data storage and

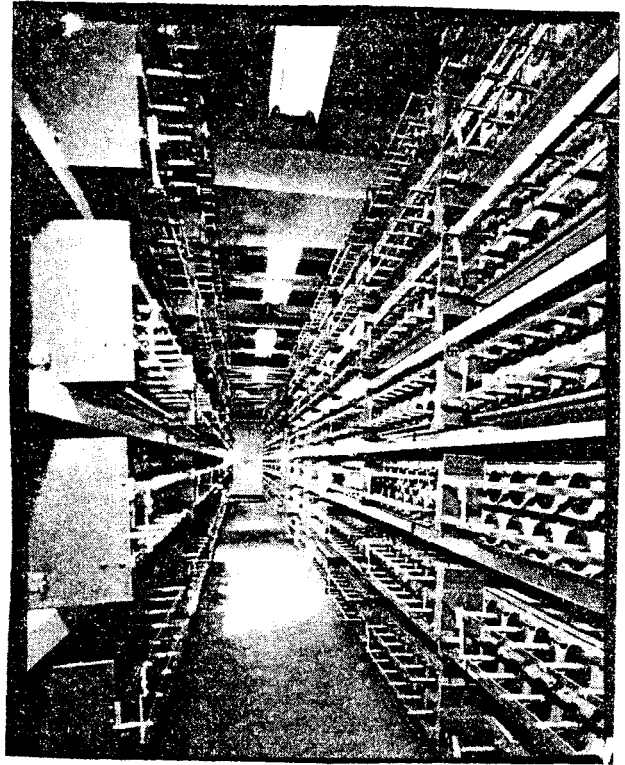


Fig. 6: A 2.5 MJ segment of the 25 MJ Shiva capacitor bank.

retrieval functions to aid in post shot troubleshooting.

With this in mind, we have developed a digital based control and diagnostic system with a high degree of electrical isolation. The control system is organized around the LSI-11 micro-computer as shown in Fig. 7. The LSI-11 internal

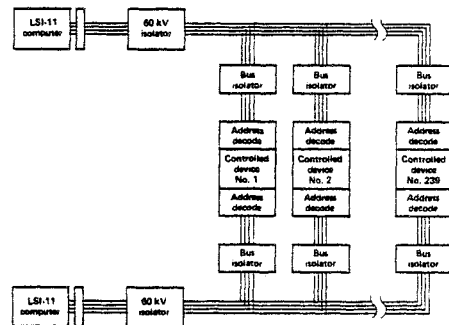


Fig. 7: Block diagram of the Shiva pulse power control system.

data bus is extended throughout the laser bay and energy storage areas to include all control and diagnostic points. As shown (Fig. 7), a 50 V, low impedance data bus extends from the LSI-11 to the interface points, 60 kilovolts of optical isolation is employed between the LSI-11 and the bus, and 3.5 kilovolts is employed between the bus and any interface point. This system has been operating successfully in the Shiva laser for the past 18 months.

For Nova, the same approach will be implemented, however, fiber-optic links will be used extensively. A prototype for the Nova control system is currently under test.

Optical Gates

A variety of optical gates have been developed for use within the laser chains. These can be categorized as either opening gates (used to prevent amplified spontaneous emission during the pump period) or closing gates (used to protect the laser from target back reflected light).

At the small aperture points (≤ 10 cm) in the laser chain, Pockels cells are used as opening gates. At apertures larger than 10 cm, Pockels cells are no longer practical because of the difficulty of growing large diameter crystals. For the large aperture applications we have developed fast rotating shutters which will be located at the focal points of the spatial filters where the beam diameter is a few millimeters.

In general, the Pockels cell circuitry supplies pulses of about 10 kV with rise times of a few nanoseconds and pulse widths of several tens of nanoseconds. The circuit¹⁰ shown in Fig. 8 is currently in use in both the Shiva and Argus lasers. As shown, a single spark gap (or thyatron) switches the shields on 20 separate cables. The pulse width is set by the pulse forming cable and the load cables feed the Pockels cells. Pulse to pulse jitter is less than 10 nanoseconds.

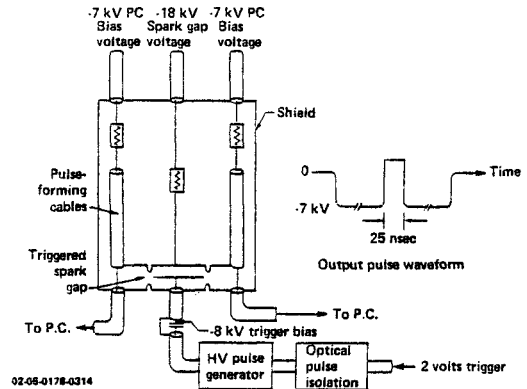


Fig. 8: Two 20-way pulsers like the one shown above are used to drive the Shiva Pockels cells. The switch can be either a triggered spark gap or a hydrogen thratron

The rise time and jitter requirements for the Pockels cells used in the oscillator switch-outs are considerably more severe. Here, a very narrow pulse is needed (≤ 10 ns) with pulse to pulse jitters of much less than a nanosecond. For these applications we have developed planar triode pulse circuitry such as shown in Fig. 9. The use of planar triodes, constant resistance networks and high frequency circuit techniques¹¹ has made possible a family of pulse amplifiers with nanosecond rise times and jitters of less than 100 ps. Typical outputs are in the range of 5 to 15 kV.

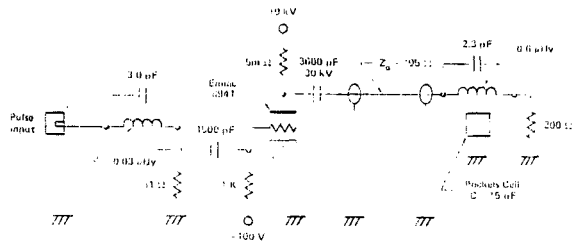


Fig. 9: Shown above is one example of a fast planar triode pulse amplifier. A number of these are currently in operation producing output voltages across Pockels cells of 3 - 5 kV with rise times of 1 - 2 ns.

Closing shutters are used to prevent target back-reflected light from reentering the laser chain and damaging optical components. Present systems employ Faraday rotator/polarizer combinations as optical gates. However, this is an expensive solution, especially at large apertures, because the energy contained in the magnetic field in the rotator glass increases directly as the volume. In addition, the rotator glass adds nonlinear path length to the beam. We have developed an alternative fast closing shutter¹² which is located at the final spatial filter pinhole. This shutter (shown in Fig. 10) rapidly injects a plasma of density greater than $10^{21}/\text{cm}^3$ (the critical density for 1.06 micron light) across the spatial filter pinhole after the outgoing light pulse has passed. A plasma velocity of about 1 cm per microsecond is required to insure the pinhole is blocked before the reflected light returns. The plasma is produced by sublimating a small mass of aluminum foil with pulsed energy from the low inductance PFN shown in Fig. 11. Eight of these PFN's are Marx charged to 50 kV and discharged through multi-channel gaps into the foil. A total energy of approximately 10 kJ is required.

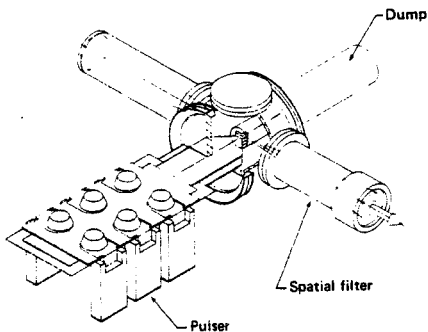


Fig. 10: A fast plasma shutter is used to inject a dense plasma across a spatial filter pinhole to block back-reflected beam from reentering the laser.

Long Term Requirements

In the near term, we are meeting the laser fusion pulse power requirements by implementing hardware solutions which are based upon existing technology of moderate extensions of existing technology. The longer term requirements involve developing



Fig. 11: Cross section of the plasma shutter pulser.

hardware which will operate reliably for 10^7 to 10^8 shots on a rep-rated basis. Further, the installed costs must approach a few dollars per joule in order for any of the inertial confinement fusion driver options to be economically feasible. This implies the development of lower cost, rep-rateable energy storage systems, reliable, high power solid state switches, and system configurations which do not involve stressing dielectrics into the corona regime. One such concept is illustrated in Fig. 12. As shown, the use of a fast discharge (50 to 100 μs) primary energy source makes possible a system which eliminates the requirement for a transfer capacitor and allows for rapid charge of the output pulse forming line.

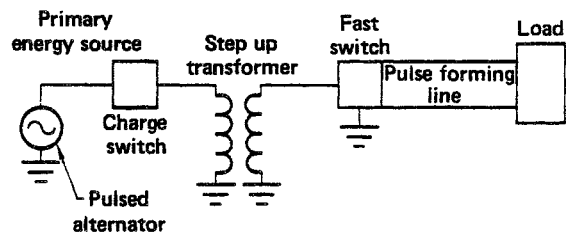


Fig. 12: The basic elements of a fast charge/discharge rep-rateable pulse power system.

A key element in this concept is the high peak power pulsed energy source and the University of Texas, Center for Electromechanics at Austin, is

currently developing such a device^{13,14} (the compensated pulsed alternator) for the Laser Fusion Program. This machine, shown in Fig. 13, is a rotating flux compressor capable of producing megajoules of output energy over a pulse width range from several milliseconds to below 100 μ s. The prototype, currently under test, is designed to drive flashlamp loads with a half millisecond pulse of about 100 kA at 6 kV. After verification of the prototype performance, a larger machine, in the several megajoule class and with an open circuit voltage of approximately 15 kV will be built. We hope to implement this technology for Phase II of the Nova project.

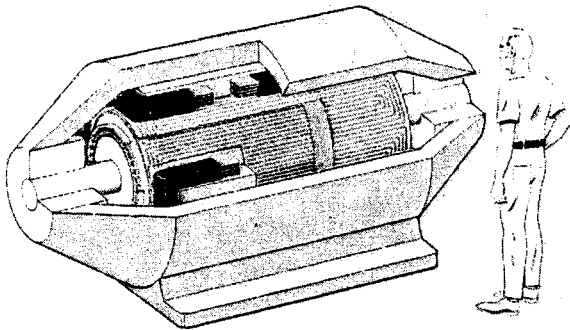


Fig. 13: Artists conception of the compensated pulsed alternator.

References

1. J. Nuckolls, L. Wood, A. Thiessen, G. Zimmerman, *Nature* **239**, 139, 142 (1972).
2. K.A. Brueckner and S. Jorna, "Laser-Driven Fusion" *Rev. Mod. Physics* **46** pp. 325-367, 1974.
3. J.L. Emmett, J. Nuckolls, L. Wood, "Fusion Power by Laser Implosion", *Scientific American* **230**, pp. 24-37, 1974.
4. C.M. Stickley, "Laser Fusion", *Physics Today*, pp. 50-58, May 1978.
5. "Nova" CP&D Final Report, Laser Fusion Program, LLL Misc. 111, March 1978.
6. "Glass Laser Power Conditioning" LLL Technology Transfer Seminar 1975.
7. J.R. Hutzler, W.L. Gagnon, "Development of a Reliable, Low Cost, Energy Storage Capacitor for Laser Pumping", *Proc. of the Int. Conf. on Energy Storage, Compression and Switching*, Nov. 1974.

8. J.P. Markiewicz and J.L. Emmett "Design of Flashlamp Driving Circuits", *IEEE Journal of Quantum Electronics*, Nov. 1966, pp. 707-711.
9. P.R. Rupert, L. Berkbigher, W. Gagnon, D. Gritton, "A High Noise Immune, Digital Control System for the Shiva Laser", *Proc. of Seventh Symp. on Engineering Problems of Fusion Research*, Oct. 1976.
10. B.M. Carder, "Driving Pockels Cells in Multi-arm Lasers", *13th Pulse Power Modulator Symp.*, June 1978.
11. M.M. Howland, S.J. Davis, W.L. Gagnon, "Very Fast, High Peak Power Planar Triode Amplifiers for Driving Optical Gates" *Proc. of 2nd IEEE Int. Conf. on Pulsed Power*, June 1979.
12. L.P. Bradley, P. Koert "Plasma Shutter for High Power Glass Lasers", *Proc. of 8th Int. Symp. on Discharges and Electrical Insulation in Vacuum*, Sept. 1978.
13. W.F. Weldon, W.L. Bird, M.D. Driga, K.M. Tolks, H.G. Rylander, H.H. Woodson, "Fundamental Limitations and Design Considerations for Compensated Pulsed Alternators" *Proc. this Conf.*
14. W.F. Weldon, W.L. Gagnon, B.M. Carder, *Compensated Pulsed Alternator*, LLL TB007, July 1978.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."